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WATER VAPOR PLASMA GASIFICATION OF PLASTIC

Growing plastic consumption leads to an ever-increasing flow of waste with a high plastic content. Plastic waste is almost entirely made from primary raw materials based on fossil fuels; therefore, plastic is recycled or disposed of. At the same time, a special group of medical waste is classified as toxic and hazardous materials, subject to additional disinfection during processing and disposal. Plastic is one of the most widely available energy sources, and gasification allows it to be converted into combustible gases. The article considers the plasma method of gasification of solid plastic waste. To implement the plasma method of processing plastic waste, including hazardous medical waste, a laboratory setup was created to process waste using plasma and study the gasification process. Water vapor, air and mixtures of water vapor with air and oxygen were used as working gases in the gasification of plastic. vapor arc plasma torches of various designs with a power of up to 160 kW were used in the plasma reactor. When selecting the geometric dimensions of the reactor working chamber, the requirement was considered that the residence time of the processing products in the high-temperature zone should be no less than the time sufficient for complete disinfection of infectious agents. This time was determined using the equation of the kinetics of the disinfection process. Calculation of the gasification process parameters was performed using an automated system of thermodynamic calculations. As a result of the calculations, the energy characteristics and equilibrium composition of the products of plastic waste processing in water vapor plasma were determined. The calculations made it possible to determine the requirements for the effective management of the plastic gasification process. The required operating mode was preliminarily estimated on a smaller-scale laboratory reactor using a 1.5 kW vapor plasma torch. It was shown that the results of thermodynamic calculations match the experiment in a heat-insulated reactor and under kinetic conditions. Optimization of the plasma gasification process will allow the development of industrial technology for processing plastic waste to produce hydrogen-enriched synthesis gas.

Key words: *plastic recycling, vapor plasma gasification of plastic, synthesis gas, plasma technologies, disinfection, thermodynamic calculations, calculation algorithm.*

Formulation of the problem. Effective waste management is an increasingly pressing challenge numerous countries face, primarily due to its profound environmental impact. In the ever-increasing waste stream, the share of plastics is growing, which is becoming a common problem because it is practically non-degradable in the natural environment. The consumption of plastic materials is vast and steadily increasing. Plastics are "one of the greatest innovations of the millennium" and have proven their reputation. The durability and strength of plastics create significant environmental challenges for waste disposal. With a degradation rate of between 100 and 1,000 years, the earliest plastics may still exist in the environment, leading to severe ecological concerns. Therefore, the first plastic invented may still exist in nature. The annual global plastic production is more than 359 million tons. And it is expected that plastic production will continue to grow exponentially in the future [1]. According to the forecast of Stubbins et al. [2], by 2035, the volume of accumulated plastic waste will equal the number of fish in the oceans. Traditional materials such as glass, wood, metal, and paper are gradually being replaced by plastic due to the shortage of raw materials in the modern era. Plastic materials are almost entirely produced from fossil fuel-based virgin raw materials (about 4 % of fossil fuels are used for this) for various applications. Because of this, plastic that ends up in waste is recycled or disposed of. First, medical waste is classified as toxic and hazardous materials. Currently, 85 % of medical products, such as intravenous bags, disposable syringes, sterile packaging, and joint replacements, are made of plastic due to its lightweight and biocompatibility. Overall, the plastic fraction constitutes a significant proportion of the total waste volume. The dominant plastic types produced globally include polyethylene (29.6 %), polypropylene (18.9 %), polyvinyl chloride (10.4 %), polystyrene (7.1 %), polyethylene terephthalate (6.9 %), polyurethane (7.4 %), along with other types of plastic, which collectively account for approximately 19.7 % of the global plastics produced. Depending on the end use of the plastic product, at some point during its life, the plastic will become waste in various sectors of commercial, industrial, and household waste. Moreover, plastic pollution poses chemical hazards, particularly with substances that contain endocrine-disrupting chemicals. Additionally, hydrophobic chemicals can adsorb environmental pollutants [3]. These chemicals can be directly ingested by organisms or leak into the environment. Potential impacts include reproductive dysfunction, low birth rates, loss of biodiversity, thyroid problems, metabolic disorders, and increased risk of hormone-sensitive cancers. Critically sensitive periods for these effects include the embryonic stages of development, with adverse outcomes observed at extremely low concentrations. Plastics also disrupt human life [1]. Chemical additives in plastics such as bisphenol A (BPA), phthalates, and brominated flame retardants (BFRs) can cause critical damage to health. Plastic pollution reduces human benefits from the oceans by 1–5 %, equivalent to an annual loss of $2,500 billion. However, plastic waste can be separated from various waste streams for subsequent recycling, recovery, and reprocessing. Therefore, areas for developing and improving plastic waste recycling technologies are relevant.

Analysis of recent research and publications. The financial implications associated with waste management technologies demonstrate significant geographic variability: US$0.003–0.23/kg for mechanical recycling, US$0.083 for chemical recycling (pyrolysis), US$0.102 for chemical recycling (gasification), and US$0.04–0.15 for incineration. According to the North American Plastic Recycling Market Report, the United States spent US$2.6 billion on recycling and US$17–24 million on incineration [4]. Until now, plastic has been predominantly recycled mechanically. Mechanical recycling is a low-cost method that does not require significant changes in the chemical structure of the materials. However, mechanical recycling has some limitations. Recycling all types of plastic, especially contaminated or made from multiple materials, is not always possible. In addition, the quality of recycled plastics may not be as high as that of primary plastics. Therefore, mechanically recycled plastics have limited applications. Alternative methods of producing fuels and feedstocks from plastic waste are also being explored [5]. The most common way to dispose of mixed plastic waste is in a landfill. India, in particular, has been a favourite dumping ground for plastic waste, mainly from industrialised countries such as Canada, Denmark, Germany, the UK, the Netherlands, Japan, France, and the US [6]. According to government data, more than 61,000 tonnes of plastic waste entered India in 1999 and 2000. However, landfills are generally less preferred overall than other waste management options. Disposal of plastic waste in landfills is very unprofitable because plastic is based on oil or natural gas and does not decompose in a landfill.

Since plastics only contain carbon, oxygen, and hydrogen atoms, incineration is still used in some energy recovery plants. Incineration is also preferable to landfilling. However, incineration is not the best option for plastic disposal. Incineration leads to problems with incinerator ash and CO_2 emissions, which cause the greenhouse effect. Incinerators dump landfill waste into the sky and create new pollutants.

When evaluating plastic recycling scenarios, pyrolysis performs better than landfill and incineration, but worse than other recycling options. It should be noted that plastic waste management analyses typically do not consider possible future formation changes: the amount of plastic entering the waste stream and its diversity. Waste streams can be reduced in response to the desire and suitability for recycling. Recycling is the best possible solution to the plastics industry's environmental problems. However, many subsequent problems need to be addressed shortly.

Task statement. The article aims to increase knowledge of the plastic waste recycling sector. This knowledge will enable the development of resource-saving technologies for recycling plastic that ends up in waste and is not used as secondary raw materials. In addition, the work aims to study the processes of water vapor plasma gasification of plastic to obtain synthesis gas enriched with hydrogen.

To achieve the set goals, it is necessary to complete the following tasks:

1. Considering the results of thermodynamic calculations of the processes of water vapor plasma gasification of plastic, develop and study a water vapor plasma reactor for gasification of plastic.
2. Study the efficiency of the reactor using water vapor, air, and a mixture of water vapor with air and oxygen as working gases.

The work's results will reduce emissions and leakage of hazardous substances from landfills into the atmosphere and groundwater, reducing the need for space for waste disposal.

Outline of the main material of the study. Currently, two primary technologies are employed for converting plastic waste into energy: pyrolysis and gasification. Pyrolysis, also known as thermal degradation, involves heating plastic waste at a temperature of about 300–650 °C in the absence of O_2, and the main product can be petroleum fuel. In gasification, plastic waste reacts with a gasifying agent (e.g., steam, oxygen, and air) at a high temperature of about 1000–1300 °C, resulting in synthesis gas. The main difference between these methods is the product obtained. Synthesis gas can be further used to produce many products, such as fuel for fuel cells, power generation, etc. Thus, gasification leads to a significant reduction in the volume of plastic waste. Consequently, this process reduces the consumption of fossil fuels.

Below is an in-depth analysis of the plasma method for recycling solid plastic waste. Since the calorific value of plastics is comparable to that of fuel, fuel production would be a better alternative. In this way, we are trying to solve the problem of plastic waste disposal and the shortage of traditional fuel, thereby contributing to the preservation of a sustainable environment.

Research on the gasification of plastic materials is relatively sparse, indicating a significant gap in academic literature. Although there are several experimental and theoretical studies [7–11] on plastic waste gasification, more detailed development of the process is an important task. A promising alternative is plasma pyrolysis combined with reforming, which allows the synthesis of gas to be obtained with a high hydrogen content and is utterly free of resin. The authors' study was conducted in this vein. Developing value-added waste recycling technologies is highly desirable, as it will increase the economic incentive for plastic recycling. Their gasification can certainly be developed into an effective recycling method for producing synthesis gas enriched with H_2 and CO. Although industrial-scale references are given in the literature, future breakthroughs in the process will require further experiments, and work on improving the design of the equipment, and optimization of the technology. Advances in this area will contribute to the improvement and broader use of gasification reactors. Although plasma technologies have a long history, their application in waste disposal is still limited. However, over the past twenty years, plasma technologies and waste disposal research have increased [12].

Plasma technology has long been used for surface treatment, coating, and disposal of hazardous waste. Still, its application in plastic waste, especially polyethylene terephthalate, has not been fully explored due to the high energy consumption of plasma gasification reactors. The treatment of plastic waste using various chemical recycling methods that convert plastic waste into fuel and other valuable products has attracted many researchers. In the paper [13], reviewing the status of the problem, competitive technologies, and opportunities for further research in the field of plastic waste gasification, the authors identify plasma gasification as a competitive technology.

To implement the plasma method of processing plastic waste, the authors created a laboratory setup designed to develop, study and demonstrate the process of processing various waste using plasma. The results obtained by the authors can be a guideline in creating such industrial installations.

Fig. 1 shows the laboratory reactor illustration for vapor plasma gasification.

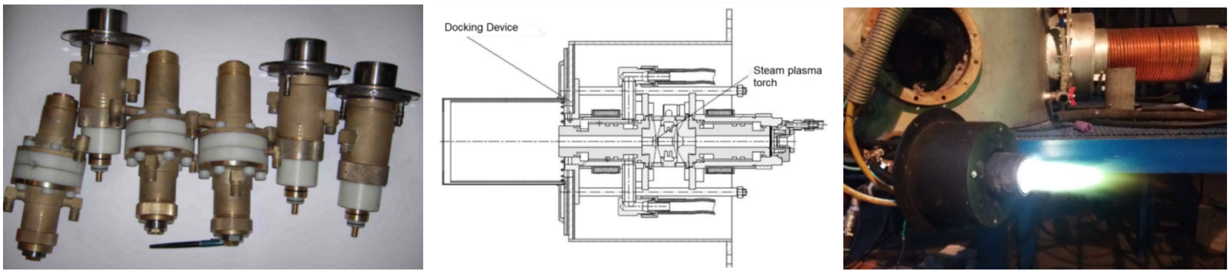
Fig. 2 shows vapor arc plasma torches in various designs with a power of up to 160 kW. The working gases used are water vapor, air, and mixtures of water vapor with air and oxygen.

The reactor (Fig. 1) can process both plastic waste and hazardous medical waste, as well as their mixtures.

To perform calculations on thermodynamic equilibrium in the process of thermal transformation of initial materials under the action of a high-temperature steam-air plasma jet, it is necessary to interpret the actual composition of the processed materials in the form of their typical representatives under the accepted concepts of chemistry. Considering the diversity of materials related to the same group of waste, a typical representative was selected for each of them, the structure of which is displayed as a gross formula. Such a representation is quite rough from the point of view of obtaining the final products of the reaction occurring under "mild" conditions; however, such a representation is justified for the analysis of high-temperature transformation (pyrolysis, conversion). For polyethylene and polypropylene containing only carbon (C) and hydrogen (H) atoms, the same gross formula was used in subsequent calculations – C_5H_{10}. For polyvinyl chloride (PVC), which contains a chlorine atom (Cl), the formula C_2H_3Cl was used. PVC has an advantage over other plastics in that it is easily mixed with additives. This gives the material a wide range of uses. Many environmental disadvantages of PVC compared to other plastics are as follows: leakage of heavy metal stabilizers and the formation of dioxins during combustion. The separate collection of PVC waste by type of product is hardly possible. The overwhelming majority of dry medicinal products contain active components in hundredths of a percent, and the basis is starch-based fillers. Starch, like cellulose, is a polysaccharide; accordingly,

a b c

Fig. 1. General view of the laboratory reactor for water vapor plasma gasification: a – reactor with a tangential plasma torch installation in section; b – 100 kW vapor plasma jet against the background of the reactor and scrubber; c – plasma torch installation with a steam preparation system in the reactor



a b c

Fig. 2. Vapor electric arc plasma torch with a power of up to 160 kW: a – vapor plasma torches with hollow copper electrodes (3 pcs.) and a tungsten hot cathode (3 pcs.) with recuperative heating of vapor before blowing into the arc chamber; b – plasma torch with hollow copper electrodes according to a three-electrode scheme and a docking device; c – plasma jet at the outlet of the docking device

the same gross formula was used for them as for dressings – $C_6H_{10}O_5$. With an average moisture content of 20 %, a specific moisture content was adopted for each group of materials under consideration. Thus, it was assumed that the amount of moisture directly introduced with them was zero when processing only polymeric materials.

In the model consideration of physicochemical, heat and mass transfer, and thermogasdynamic processes occurring at elevated temperatures, problems arise regarding finding the reaction products' composition and determining the thermodynamic and transport properties of high-temperature surroundings. These properties, in turn, also depend on the composition of the working fluids – multi-component mixtures of dissociating gases and individual condensed phases, and are functions of state: temperature, pressure, specific volume, etc. As a rule, considering kinetic, heat, and mass transfer processes at elevated temperatures, which are already at the stage of setting the modeling problem, leads to significant difficulties. Detailed calculation schemes are usually associated with mathematical complexities and the absence of the necessary closing initial data, and in simplified models, with excessive schematization of the process. In this regard, thermodynamic simulation methods have gained tremendous popularity. They assume that the working fluid in the processes under consideration forms a conditionally closed, isolated system in which local phase and chemical equilibrium have been established. In this approximation, the state of the system is determined only by the content of chemical elements in it and the value of two state parameters.

The validity of using the thermodynamic equilibrium approximation is justified by the high level of energy concentration in the volumes under consideration and, consequently, the high rates of transformation processes, which instantly bring the environment to a state of local equilibrium.

To calculate the specific energy costs for high-temperature processing of plastic waste, in addition to knowing the parameters of the equilibrium composition corresponding to the selected temperature of the process, it is necessary to understand the standard enthalpy of formation of the initial materials to be processed. Unfortunately, such data are unavailable in the literature for many of these components. Therefore, for many substances consisting mainly of hydrocarbons, an approach based on the well-known empirical formula of D.I. Mendeleyev for calculating the heat of combustion of substances was chosen as an indirect method for determining the standard enthalpy of formation.

One of the basic requirements for processing hazardous and harmful waste is to ensure its reliable disinfection. The technology being developed involves conducting the waste processing process in the range of 1000–1600 °C. Therefore, when choosing the geometric dimensions of the working chamber of the reactor, it is necessary to ensure that the condition is met, which consists in the fact that the residence time of the processed products in the high-temperature zone should be no less than the time sufficient for the complete disinfection of infectious agents contained in the original products.

Since at the planned high temperatures decomposition reactions of almost all materials proceed with high speed to the end, a gross equation of the following form was chosen to describe the kinetics of the decontamination process:

$$\frac{dx}{d\tau} = k(T) \bullet x,$$

where x is the fraction of non-disinfected agents, $k(T)$ – rate constant depending on temperature T K, sec^{-1}, τ – time, sec.

The solution of which

$$x(\tau) = \exp\left(-k(T) \bullet \tau\right)$$

allows to determine the degree of decomposition at selected temperature and reaction time.

To evaluate the generalized dependence of the reaction rate on temperature calculated for the most resistant materials, it was assumed that at a temperature of 100 °C and a 2 second exposure time, the proportion of virulent agents retaining viability is 0.99999, and at 1100 °C and the same exposure time – 10^{-5}, which practically coincides with the condition of complete disinfection.

The result is for the rate constant in the form of an Arrhenius dependence:

$$K(T) = A \bullet \exp\left(-\frac{E}{R_E \bullet T}\right).$$

We have: $A = 1049,5\ sec^{-1}$; $E = 59421,1\ kJ/kmol$; $R_E = 8,314\ kJ/(kmol \cdot K)$.

The obtained data allow estimating the required residence time of infected medical waste in the reaction zone for different temperatures (see Table 1).

Table 1

Dependence of the required residence time of infected medical waste in the reaction volume on the temperature of the decontamination process

t, °C	T, K	k(T), сек-1	τ, сек
1000	1273	3,82435294	3,010426
1100	1373	5,75646499	2
1200	1473	8,19671816	1,404578
1300	1573	11,1585897	1,031755
1400	1673	14,6407443	0,786362
1500	1773	18,6299391	0,61798
1600	1873	23,1039009	0,498311

Thermodynamic calculation of the process of recycling waste of various compositions using a low-temperature plasma jet as an external heat source and reaction components requires knowledge of its main quantitative indicators. In the case under consideration, the plasma jet can be formed both by using only water vapor and water vapor and air in a particular proportion. Moreover, in the latter case, not only can atmospheric air be used, but air enriched with oxygen can also be used, up to technical oxygen. The calculation is based on the energy balance method using the original components' total enthalpy and the resulting plasma jet of a given temperature.

The enthalpies were calculated using the automated thermodynamic calculation system TERRA. The initial enthalpy of water vapor corresponded to the total enthalpy of saturated water vapor at a temperature of 100 °C, and the enthalpy of air corresponded to the total enthalpy at 20 °C. The calculations were performed for various water/air ratios in the plasma jet, using atmospheric air ($\eta = 0.23$, where η is the mass fraction of oxygen) and oxygen-enriched air ($\eta = 0.55$).

One of the most thermodynamically stable products of high-temperature plasma waste treatment is carbon monoxide – CO. Its formation can occur due to the oxidation of free carbon by oxygen contained in the plasma jet and oxygen released during the decomposition of a water molecule. The reactions indicated are as follows:

$$H_2O \rightarrow H_2 + 0,5O_2 \ (242334 \ kJ/kmol),$$

$$C + 0,5O_2 \rightarrow CO \ (-124413 \ kJ/kmol).$$

The energy ΔQ_1 that must be expended to obtain 1 kg of oxygen by decomposing water is: $\Delta Q_1 = 242334/16 = 15146$ kJ. In this case, 8/9 kg of oxygen is obtained from 1 kg of water.

The amount of energy ΔQ_2 released during carbon oxidation by oxygen is: $\Delta Q_2 = (8/9) \cdot 124413/16 = 6912$ kJ.

Thus, the carbon oxidation by oxygen contained in 1 kg of water (the reaction of carbon conversion by water) is described by the overall reaction in the form:

$$C + H_2O \rightarrow H_2 + CO$$

requires energy expenditure

$\Delta Q_{H2O} = \Delta Q_1 - \Delta Q_2 = 15146 - 6912 = 8234$ kJ.

Oxidation of carbon directly by oxygen contained in the plasma jet releases energy (per 1 kg of oxygen): $\Delta Q_{O2} = 124413/16 = 7776$ kJ.

Using the results of calculating the parameters of the plasma jet for specific temperatures and at different water/air ratios, it is possible to construct graphs of the dependence of the energy that will be released in the reaction volume during the combined reaction of carbon conversion and oxidation on the temperature of the plasma jet (Fig. 3, 4).

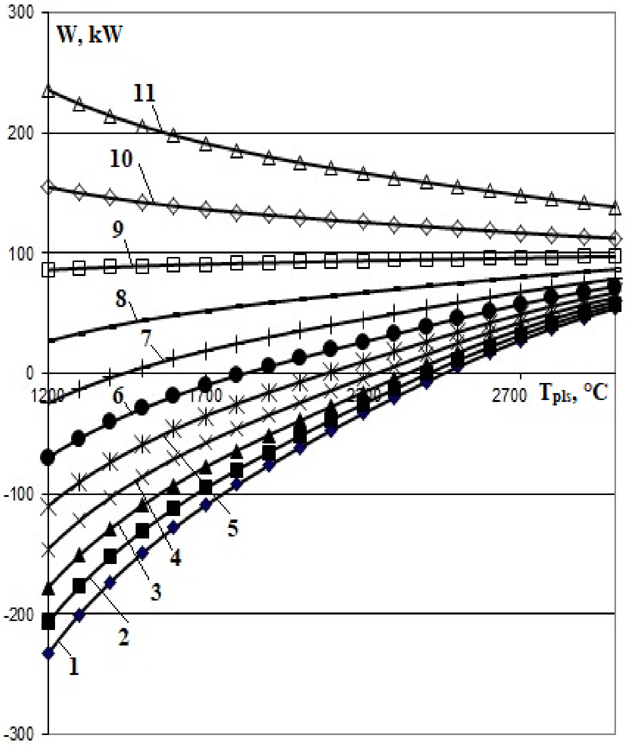


Fig. 3. Energy balance of the process of carbon oxidation by a vapor – air plasma jet at different water vapor/air ratios: 1 – 1/0; 2 – 0,9/0,1; 3 – 0,8/0,2; 4 – 0,7/0,3; 5 – 0,6/0,4; 6 – 0,5/0,5; 7 – 0,4/0,6; 8 – 0,3/0,7; 9 – 0,2/0,8; 10 – 0,1/0,9; 11 – 0/1

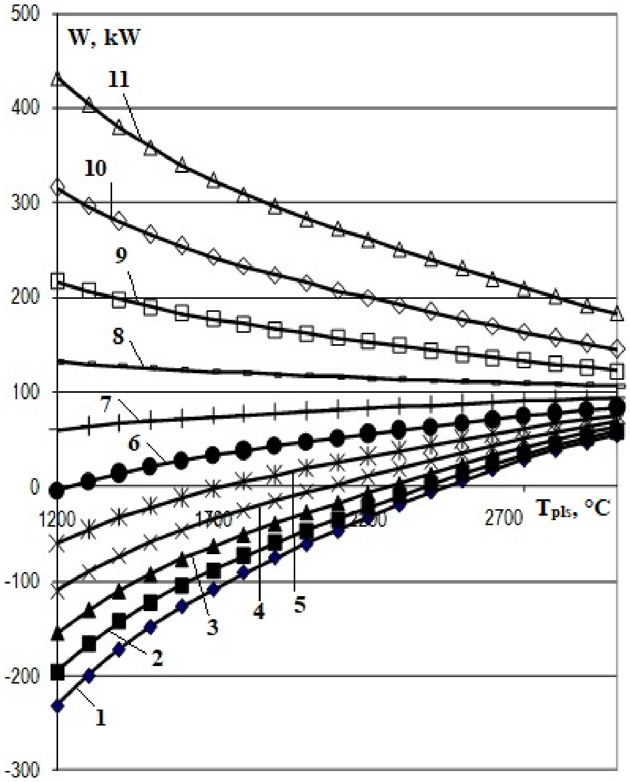


Fig. 4. Energy balance of the process of carbon oxidation by a vapor -air plasma jet at different ratios of water vapor/oxygen-enriched air: 1 – 1/0; 2 – 0,9/0,1; 3 – 0,8/0,2; 4 – 0,7/0,3; 5 – 0,6/0,4; 6 – 0,5/0,5; 7 – 0,4/0,6; 8 – 0,3/0,7; 9 – 0,2/0,8; 10 – 0,1/0,9; 11 – 0/1

The energy characteristics and equilibrium composition of the products of plastic waste processing with steam-water plasma were obtained under the following restrictions: no soot formation; all steam comes with the plasma jet.

Several calculation algorithms have been developed to calculate the recycling processes of plastic waste.

The algorithm for calculating the process of recycling waste at a given power and temperature of the plasma jet, as well as the composition of its constituents, assumes the following sequence:

1. We calculate the plasma jet's composition, total, and component consumption based on a given set of plasma-forming substances, the plasma torch's thermal power, and the plasma jet's temperature (Table 2). The following components were considered: H, H_2, H_2O, Cl, Cl_2, HCl, N_2, NH_3, Cc, CO, CO_2, CH_3, CH_4, C_2H, C_2H_2, C_2H_3, C_2H_4, C_2H_6, C_3H, C_4H_2, CHO, CH_2O, CH_2O_2, CH_2Cl, CH_3Cl, C_2HCl, CN, C_2N_2, HCN, HNC, C_3NH, C_5NH, C_7NH, C_9NH, N_2C, ClCN.

As an example, Table 2 shows various calculation options for such polymeric materials as polyethylene and polyvinyl chloride with the following parameters:

– unit capacity – up to 100 kg/h;
– plasma torch power – 100 kW;
– plasma jet temperature (T_{pls}) – 2000–3000 °C;
– water/air or oxygen-enriched air ratio of components forming the plasma jet – 0÷1 (weight fractions);
– temperature in the reaction volume (T_{rv}) – 800, 1000, 1200, 1400, 1600 °C.

2. Calculate the enthalpy values for forming processed substances.

3. Based on the given composition of the processed substances and the enthalpies of their formation (item 2) and the composition of the plasma jet at its given temperature (item 1), we calculate the parameters of the reaction products for different values of temperature in the reaction volume.

4. Based on the energy balance condition, we determined the actual temperature in the reaction volume corresponding to the thermal power of the plasma jet.

5. For the actual temperature of the reaction volume, we specified the composition of the reaction products.

When calculating the maximum plant capacity, general and additional limitations were considered.

Table 2

Calculation options for polyethylene (PE) and polyvinyl chloride (PVC)

#	PE	PVC	H_2O	O_2	T_{pls}	T_{rv}	V	H_2	CO	CO_2	N_2	HCl	Cc
	kg/h				°C		m^3/kg	Mass fractions					
1	17	8,5	27,3	-	2800	1100	9,7	0,108	0,783	0,005	-	0,094	-
2	40	20	15	-	3000	1100	7,8	0,107	0,31	-	-	0,155	0,42
3	20	10	27	6,21	2600	1200	8,4	0,07	0,57	0,014	0,25	0,07	-
4	40	20	15,5	3,6	3000	1100	7,3	0,09	0,33	-	0,13	0,13	0,32
5	30	15	34	18,8	2400	1200	8,3	0,07	0,62	0,04	0,14	0,08	-
6	42	21	15,6	8,6	3000	1200	8	0,09	0,42	-	0,07	0,13	0,29

v – specific volume of processed products, m^3/kg.

General limitations for all plant operating modes are:

a) the lower temperature of the reaction volume is the temperature below which the conversion reactions occur at a low rate, and below which waste disposal is not guaranteed;

b) the upper temperature of the reaction volume is limited mainly by the materials' heat resistance and, in some cases, by the formation of undesirable substances.

Additional limitations can be applied if a condition is imposed for the absence of the formation of certain substances, such as the presence or absence of carbon in condensed form (soot).

The algorithm for determining maximum productivity in the absence of soot formation assumes the following sequence:

1. For a sequence of plasma jet temperatures (in the range of 2000–3000 °C) and at different water/ air (oxygen-enriched) ratios, the maximum (for these plasma jet parameters) amount of processed substances was selected, at which soot formation does not occur.

2. Based on the results obtained in step 1, a graph of the dependence of the maximum productivity of the installation on the plasma jet temperature is constructed. At the same time, a graph of the dependence of temperatures in the reaction volume corresponding to the maximum productivity as a function of the plasma jet temperature is constructed.

3. Based on the restrictions on the permissible range of temperature changes in the reaction volume, the allowable range of the plasma jet temperature was determined, within which the maximum possible productivity should be determined.

4. Simultaneously with the graphs of step 2, the dependences of the change in the proportion of components in the total flow of reaction products (of interest to the researcher) on the plasma jet temperature are constructed. Such graphs make it possible to introduce additional restrictions on the permissible range of change of the plasma jet, defined in step 3, where the concentration of some components goes beyond the allowable limits.

Similar graphs can be constructed for different variants of plasma-forming substance ratios.

The algorithm for determining maximum productivity without restrictions on the soot formation process is similar to the previous one. Still, the permissible range of operating parameters is significantly expanded in this case. It should be noted that the productivity of the waste processing plant increases considerably with the same nominal power as the plasma torch (100 kW).

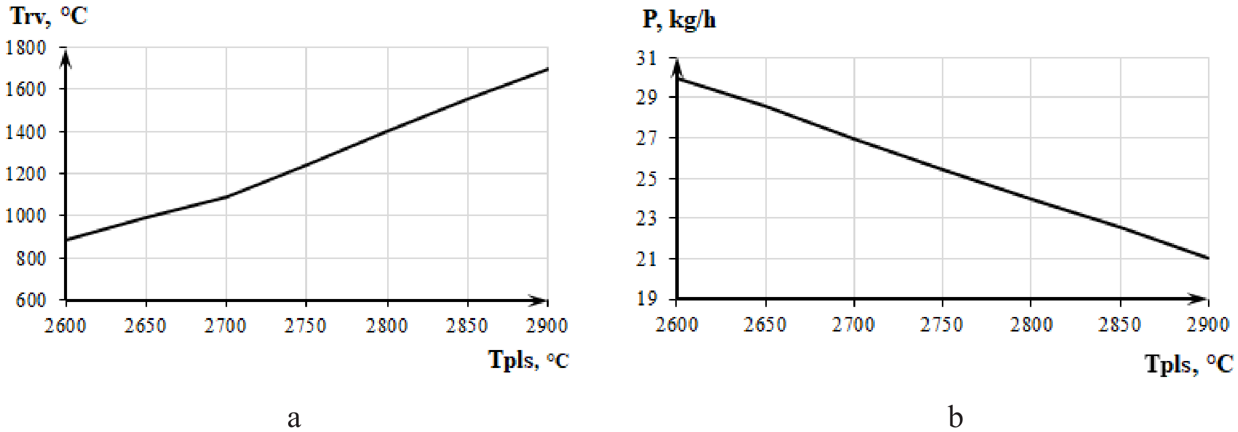
The calculations performed using the proposed algorithms obtained the dependencies presented in Figs. 5 (a, b), 6, 7, and 8.

The calculations have shown that:

1. When the amount of water vapor in the reaction space corresponds to the stoichiometry of the processed products, synthesis gas of optimal composition is formed, soot formation is excluded, and the probability of formation of undesirable harmful products (methyl chloride, etc.) is reduced. Taking this into account, an excess of water vapor is desirable.

2. Increasing the water supply with the plasma jet, with limited plasma torch power, reduces its temperature, leading to a corresponding drop in temperature in the reaction volume, slowing down endothermic reactions, i.e., decreasing plant productivity.

3. Limiting the water supply through the plasma torch (15 kg/h) with compensation for the missing water according to stoichiometry due to additional



a b

Fig. 5. Calculated dependences of the temperature in the reaction volume (a) and maximum productivity (b) on the temperature of the vapor – air plasma jet (water/air 0.8/0.2) under the condition Cc = 0

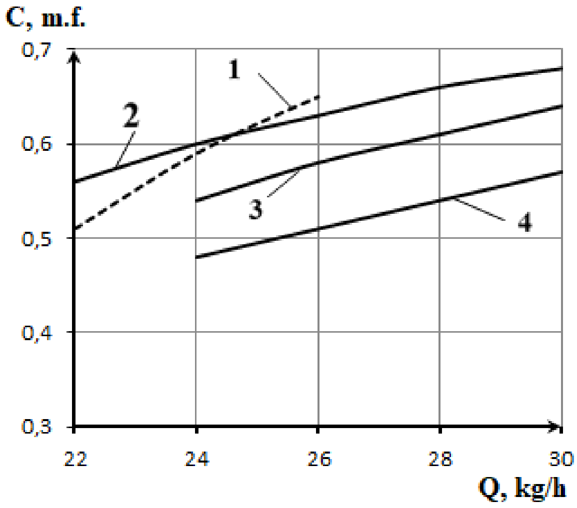


Fig. 6. Calculated dependence of CO concentration on the load at different temperatures of the vapor – air (water/air – 0.7/0.3) plasma jet: 1 – 2800 °C; 2 – 2700 °C; 3 – 2600 °C; 4 – 2500 °C

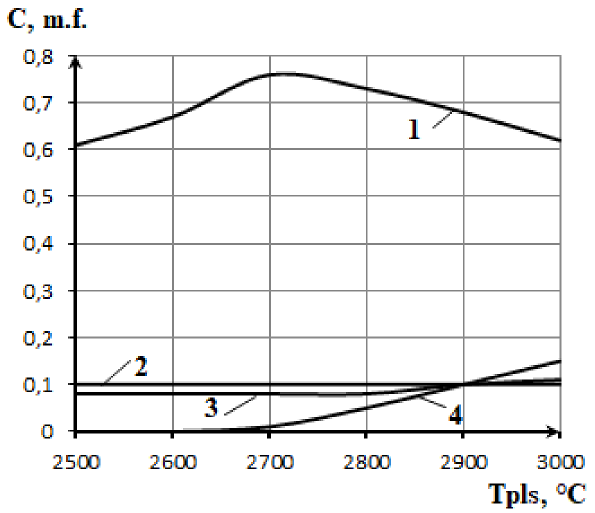


Fig. 7. Calculated dependence of the concentration of the main reaction products on the temperature of the water vapor plasma jet: 1 – CO; 2 – H_2; 3 – HCl; 4 – Cc

Fig. 8. Calculated dependence of water consumption on the average mass temperature of the plasma jet

superheated steam up to 500 °C does not provide a noticeable gain, since superheating steam from 100 °C to 500 °C does not require a large amount of energy (the main energy is spent on evaporation of water).

4. Removing restrictions on soot formation allows for a significant increase in the plant's productivity, but it is necessary to ensure the capture of soot particles at the outlet. In this case, soot can be considered a valuable by-product in high demand.

5. Adding air (or oxygen-enriched air) to the plasma jet in addition to water vapor, while maintaining the required balance in terms of maintaining the required temperature of the plasma jet, allows to increase the productivity of the plant due to the occurrence of oxidative (exothermic) reactions, but at the same time the quality of the synthesis gas decreases (its calorific value decreases). Naturally, when adding air to the plasma jet, especially oxygen-enriched air, the required temperature in the reaction volume can be maintained at a significantly lower (by 500–600 °C) temperature of the plasma jet.

6. When processing polymeric materials, in the absence of its own moisture, with the removal of the limitation on soot formation, the plant's productivity is 2.4 times greater than without the restriction. A separate water supply (15 kg/h with the plasma jet, and the remaining 12.3 kg/h separately at a temperature of 500 °C) is equivalent to increasing the plasma torch power by 2.7 kW, which does not provide a noticeable gain. Adding air to the plasma jet steam raises the reaction volume's temperature and increases the productivity by ~ 1.3 times and adding oxygen-enriched air increases the productivity by 2 times.

7. When processing a mixture of medical waste, provided that its own moisture is up to 20 %, the

problem of soot formation does not arise. When using steam-water plasma with a plasma torch power of 100 kW, the plant's productivity is up to 52 kg/h (considering its own moisture). When air is added to the plasma jet, productivity increases by 1.2 times; when oxygen-enriched air is added, productivity increases by 1.4 times.

Steam gasification reactions typically operate at high temperatures to achieve optimal reaction rates because they are highly endothermic. In a typical steam gasifier, at least 35 % of the feedstock must be burned to achieve the process, which results in the formation of additional harmful compounds. When considered comprehensively, plasma gasification was identified as the most environmentally friendly method for plastic waste treatment from ecology, economics, and strategic vision perspectives. A roadmap for economic and environmental vision was presented, which resulted in a financial profit with an 80 % rate of return, a payback period of 1.2 years, and a gross margin of 129 % for a 120 t/day plasma reactor [14, 15]. However, optimization is required for industrial scaling.

The energy-efficient laboratory vapor-plasma setup (Fig. 9) includes a steam plasma torch (Fig. 2a) with a power of up to 160 kW, operating on water vapor, air, and a mixture of water vapor with air or oxygen. The plasma torch is connected to the reactor tangentially to the cylindrical working chamber (Fig. 1a) through a docking device (Fig. 2 b, c). Atmospheric pressure plasma jets are the primary tool for gasification. However, the small size of atmospheric pressure plasma jets limits their use for small-scale material processing. To solve this problem, the authors developed a docking device for increasing the plasma volume without additional power sources or circuits [17].

In this case, additional gas flows are located orthogonally in the direction of jet propagation, which leads to the formation of new plasma regions along these flows. This approach increases the plasma volume, increasing the effective area available for surface interaction. The setup contains a plasma torch power source based on an adjustable thyristor rectifier with an open-circuit voltage of 600 V and an operating current of up to 300 A, waste feed and dosing mechanisms with a capacity of up to 100 kg/h, ash removal, a scrubber for cleaning synthesis gas (Fig. 1 b), and control and monitoring systems. The reactor contains a cylindrical chamber with an internal wall made of heat-insulating ceramics. Plasma is introduced above the surface of the waste material tangentially so that the main heating of the material occurs by radiation from the chamber wall. Partial supply of oxidizer (superheated water vapor with oxygen or air) occurs through the grate. At the reactor outlet, a heat exchanger (gas-water) is provided for the recovery of thermal energy of the outgoing synthesis gas. Crushed plastic waste is fed to the movable grate by a screw feeder. A sluice gate is provided to prevent the release of flammable gases. The temperature of the gases leaving the reactor is maintained at 800–1200 °C by regulating the arc current of the plasma torch. Before switching on the waste feed, the reactor is heated to a wall temperature of 1300–1500 °C by a plasma torch operating in air. Switching to water vapor or a mixture of steam and oxygen occurs with waste feed. The reactor operates with an excess pressure of 20–50 Pa. Slag is removed through a water seal, eliminating atmospheric air suction.

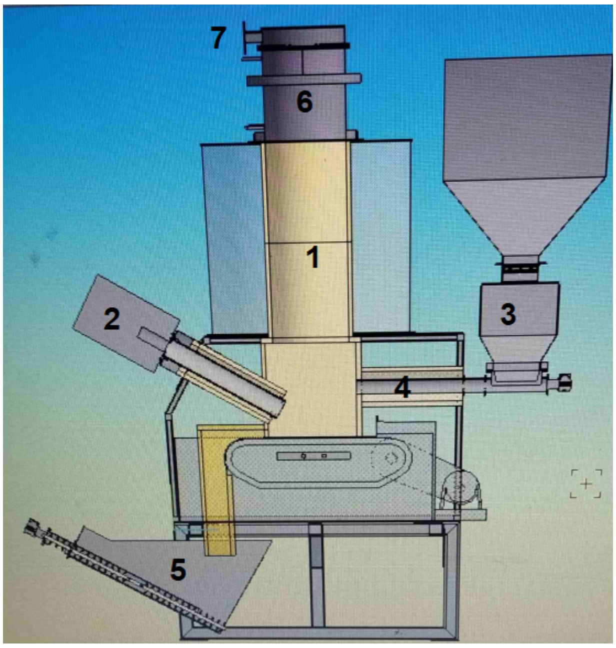
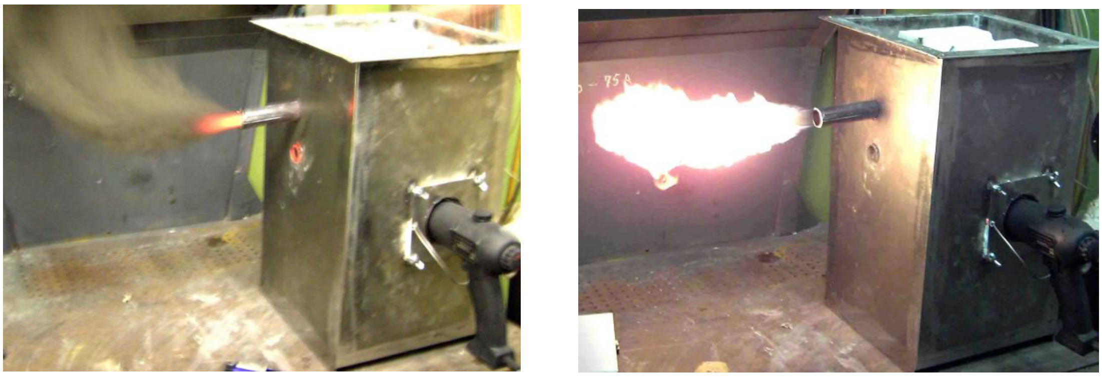


Fig. 9. Schematic diagram of the plastic gasification plant
1 – reactor; 2 – plasma torch; 3 – loading device with a system of locks; 4 – device for screw feeding of raw materials; 5 – device for removing ash; 6 – heat exchanger; 7 – device for the outlet of synthesis gas

The gasification of plastic waste (a mixture of polyethylene with polyvinyl chloride at a ratio of 2:1) was carried out in three variants: using only water vapor, a mixture of water vapor with air, and a mixture of water vapor with air enriched with oxygen to 50%. In all cases, the consumption of plastic waste was maintained to exclude soot formation.

The required operating mode was preliminarily assessed visually based on the absence of smoke in



a b

Fig. 10. Vapor plasma gasification of plastic waste in a laboratory setup with a 1.5 kW plasma torch, reactor wall temperature at the outlet is 950 °C: a – lack of vapor (presence of soot formation), b – stoichiometric ratio (absence of soot formation)

the laboratory reactor's exhaust gases (Fig. 10 a, b) using a 1.5 kW vapor plasma torch.

Vapor plasma gasification has been studied in general, and the results of thermodynamic calculations agree with the experiment in a thermally insulated reactor under kinetic conditions. A description of energy-efficient vapor plasma technologies for processing plastic waste can be found in [16–18]. Plastic gasification is a fast reaction at optimal temperatures with a residence time of up to 1 sec for volatile products. However, scaling is limited by increasing the required plasma torch power with increasing process productivity. Heat recovery from exhaust gases at the reactor inlet is also useful. Perhaps the only solution to the problem is to combine the thermal energy introduced into the reactor from the plasma torch and partially oxidize the raw material with air (oxygen-enriched air or oxygen). It is noteworthy that in this case, a combined two-stage process can be implemented in one reactor. The plasma energy mainly provides effective high-temperature (1300–1500 °C on the reactor wall) conversion of solid waste into the gas phase with a dispersed component in the form of a vapor phase of decomposition products, soot and resinous compounds. This entire mixture is converted to synthesis gas with a temperature of 900–1100 °C at the reactor outlet. In this case, nitrogen and carbon dioxide will appear in significant quantities in the synthesis gas, and the percentage of hydrogen will decrease. However, this mode allows for the increase of reactor productivity without soot formation and, as a result, an increase in the synthesis gas yield with a decrease in the required specific power. The results of experiments on the gasification of a mixture of polyethylene with polyvinyl chloride in a reactor (Fig. 1) are shown in Fig. 11. The useful power of the plasma jet was maintained at 100 kW for three operating modes:

1. working gas – water vapor 27 kg/hour, productivity 25 kg/hour (curves 1.1 and 2.1 in Fig. 10);
2. working gas – water vapor 27 kg/hour + air 27 kg/hour, productivity 35 kg/hour (curves 1.2 and 2.2 in Fig. 10);
3. working gas – water vapor 34 kg/hour + air enriched with oxygen 0.5/0.5 34 kg/hour, productivity 45 kg/hour (curves 1.3 and 2.3 in Fig. 10).

As Fig. 11 shows, regulating water vapor has virtually no effect on the output of hydrogen and carbon monoxide but serves to suppress soot formation and the output of resinous compounds. The relative amount of H_2 and CO decreases, the ratio remains

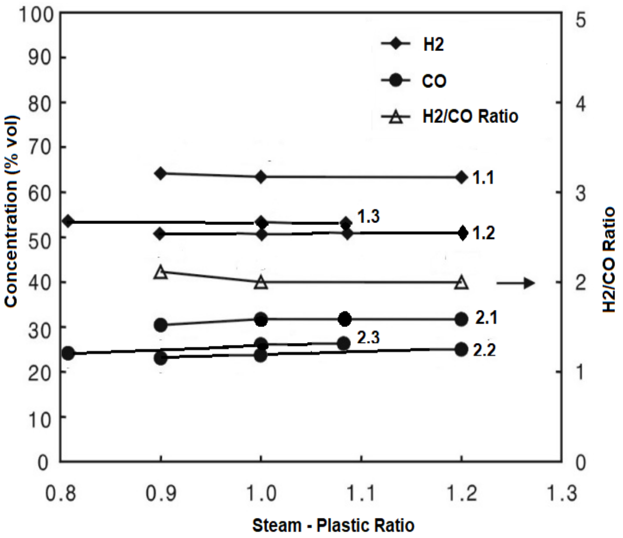


Fig. 11. Concentrations of H_2 and CO gases depending on the modes of vapor plasma gasification of a mixture of polyethylene with polyvinyl chloride in accordance with Table 2: 1.1, 2.1 – vapor plasma gasification; 1.2, 2.2 – plasma gasification in a mixture of vapor with air; 1.3, 2.3 – plasma gasification in a mixture of vapor with oxygen-enriched air

virtually unchanged, and the production of synthesis gas increases.

Generally, the first phase of solid gasification involves heating, evaporation, and reaction of carbon with air, oxygen, and vapor at a temperature of 400–700 °C or higher, providing the necessary heat from plasma and exothermic reactions. Using a vapor plasma gasification system, plastic waste is decomposed to form hydrogen (~ 60 %) and CO (~ 30 %) at the reactor outlet with a steam/plastic ratio of (~ 1/1) at a temperature of ~ 1000 °C using an electric arc vapor heater.

Conclusions. A unit for the gasification of plastic waste using plasma has been developed and studied. Water vapor, air, and mixtures of water vapor with air and oxygen were used as working gases during plastic gasification. The geometric dimensions of the reactor working chamber were determined considering the requirement for the time of complete disinfection of hazardous medical plastic waste in the high-temperature zone. The effect of operating conditions on the productivity of the gasification plant was studied, and the composition and yield of synthesis gas were estimated. It was shown that the process occurs without soot formation with excess water vapor. Increasing the vapor supply and temperature can improve gasification's reactivity and productivity.

The sustainability of any plastic waste management system depends on many factors. When selecting the latest technologies, plasma gasification should be considered a leading waste management option. There is experience and great potential for developing and applying plasma gasification technology with energy recovery. Undoubtedly, vapor plasma gasification can be developed into an industrial technology for recycling plastic waste into hydrogen-rich synthesis gas. Complex waste can be converted into usable energy products. However, if the safety issues of plasma gasification technologies have a positive answer, then whether they can be made reasonable awaits their solution, since these approaches so far lead to the exploitation of more natural resources rather than resource and energy conservation. The plasma gasification reactor should be designed in such a way that it is suitable for mixed plastic waste from small and medium production. In addition, technology optimization should reduce capital investment and operating costs and thus increase the economic viability of the process.

Thus, plastic gasification may be a promising method for reducing environmental pollution and generating energy. The resulting synthesis gas can be converted into heat, electricity, biofuel, hydrogen, biomethane, etc.

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ПАРОПЛАЗМОВА ГАЗИФІКАЦІЯ ПЛАСТИКА

Зростання споживання пластику призводить до постійного збільшення потоку відходів з високим вмістом пластмас. Пластикові відходи майже повністю виготовлені з первинної сировини на основі викопного палива, тому пластик переробляють або утилізують. При цьому особливу групу складають медичні відходи, які відносяться до токсичних та небезпечних матеріалів, що підлягають їхньому додатковому знезараженню при переробці та утилізації. Пластик є одним із найбільш широкодоступних джерел енергії, газифікація якого дозволяє перетворити його на горючі гази. У статті розглянуто плазмовий метод газифікації пластикових твердих відходів. Для реалізації плазмового методу переробки пластикових відходів, у тому числі і небезпечних медичних відходів, створено лабораторну установку, призначену для переробки відходів з використанням плазми, а також для дослідження процесу газифікації. Як робочі гази при газифікації пластику використовувалися водяна пара, повітря і суміші водяної пари з повітрям і киснем. У плазмовому реакторі використовувалися парові електродугові плазмотрони у різному виконанні потужністю до 160 кВт. При виборі геометричних розмірів робочої камери реактора враховано вимогу, що час перебування продуктів переробки в зоні високих температур має бути не менше часу, достатнього для повного знезараження інфекційних агентів. Цей час визначено з використанням рівняння кінетики процесу знезараження. Розрахунок параметрів процесу газифікації виконано за допомогою автоматизованої системи термодинамічних розрахунків. В результаті проведених розрахунків визначено енергетичні характеристики та рівноважний склад продуктів переробки пластмасових відходів у пароводяній плазмі. Проведені розрахунки дозволили визначити необхідні вимоги ефективного ведення процесу газифікації пластику. Попередньо потрібний режим роботи оцінювали на лабораторному реакторі меншого масштабу при використанні парового плазмотрона потужністю 1,5 кВт. Показано, що результати термодинамічних розрахунків добре збігаються з експериментом у теплоізольованому реакторі та при виконанні кінетичних умов. Оптимізація процесу плазмової газифікації дозволить розвинути їх у промислову технологію переробки пластикових відходів з отриманням синтезу газу, збагаченого воднем.

Ключові слова: *переробка пластику, пароплазмова газифікація пластику, синтез газ, плазмові технології, знезараження, термодинамічні розрахунки, розрахунковий алгоритм.*